A NEW SEAT SYSTEM DEVELOPED BY K-D NECK MODEL ® TO REDUCE WHIPLASH INJURIES

Masatoshi Tanaka
Daihatsu Motor Co.,LTD
Japan

Hiroaki Yoshida, Sadami Tsutsumi
Kyoto University
Japan
Paper No.203

ABSTRACT

Recently various researchers have attempted to clarify the mechanism of whiplash injuries, but the mechanism is not yet wholly understood. This is because researching tests are difficult to reproduce actual rear-end automobile accidents.

To solve this problem, we made experimental and numerical analyses.

First of all, we developed a new biomechanical cervical model named as "K-D neck model" to reproduce human neck movements at low-speed rear-end collisions. Shear displacements in the plane of the intervertebral disks were observed.

Secondary, in order to verify the biomechanical fidelity of the K-D neck model, numerical analyses using finite element models with both active and passive muscle elements were conducted to compare among each lateral head displacement of the cadaver, the volunteer and the K-D neck model.

To reduce whiplash injuries, the new headrestraint system equipped on a car seat was developed. The headrestraint swings forward after low-speed rear-end collisions. By the sled tests, we measured the neck's lateral and longitudinal cervical movements in every 1 millisecond, and observed that the faster support of the dummy head was effective to reduce both lateral and longitudinal displacements between each cervical vertebra.

INTRODUCTION

The percentage of accidents resulting from rear-end collisions in recent years accounts for 27.5 percent of all vehicle accidents in Japan (Figure 1.). Though the death rate is low in these type of accidents, the minor injury rate is very high (Figure 2.). About 90 percent of these minor injuries are neck injuries and the so-called "whiplash injury" which is prone to occur in these low-speed rear-end collisions makes up a large share of these injuries

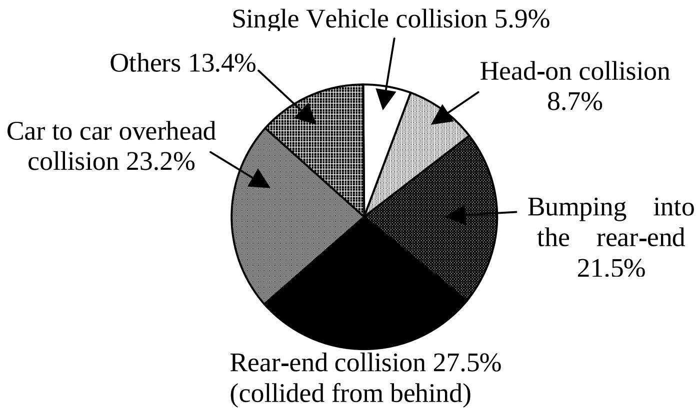


Figure 1. Accident pattern ratio in Japan (1992 JARI)

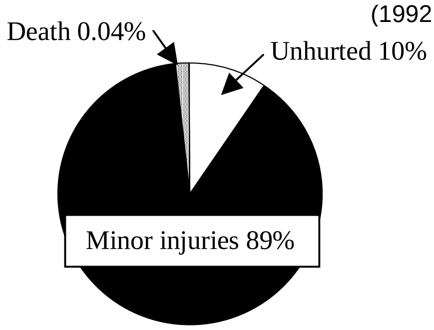


Figure 2. Driver injury level in rear-end collision (1992 JARI)

In year 2000, 530000 men were suffered from neck injury and the amount of insurance payment is 3.0 billion dollars (equal to 350 billion yen) a year.

The mechanism of whiplash injuries is not yet wholly understood. To investigate the mechanism of whiplash injuries in low-speed rear-end collision, we hold two analyses.

1. Experimental analyses with the new biomechanical cervical model (named as K-D Neck Model)
2. Numerical analyses with a finite element method (FEM)

NECK MODEL COFIGURATIONS

The neck of the human body (Figure 3.) is composed of cervical vertebrae, ligaments, intervertebral disks, muscles and the other items.

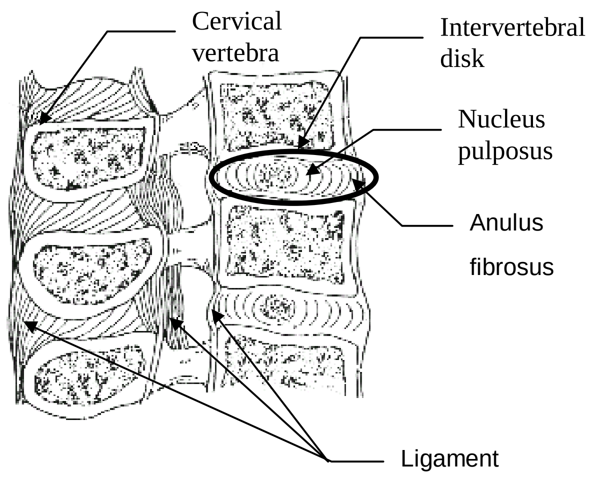


Figure 3. Structure of a human body neck

Figure 4. shows the structure of the K-D Neck Model .The shortest response period of muscles against stimulation is approximately 150 to 250ms. It is obvious that effects by muscles within 150ms can be excluded. This model is therefore comprised of several elements : cervical vertebraes, ligaments, intervertebal disks, and other soft tissues. An integrated, polymerized artificial material with biomechanical properties that closely resemble the matching parts in the human body is used.

Substituting the cervical vertebrae

A copy of the cervical vertebrae is made from polyurethane based on a medical model of the cervical vertebrae*.

Substituting the ligaments

Three-dimensional textiles** are used for the ligaments. These three-dimensional textile structures are comprised of multifilaments, cotton thread, and coupling threads such as monofilaments.

Substituting the intervertebral disks

Silicone rubber is used.

Other items

The cervical ligaments are covered with colorless silicone rubber*** in view of the soft tissue structures around the ligamentous neck. The colorless, transparent rubber allows to observe movements of the K-D Neck Model.

Figure 4. K-D Neck Model

* Cervical vertical model for a medical science, Synthes Ltd.

** Cubic-eye HA6003, Yunitika Co.,Ltd.

*** RTV Rubber KE1603, Shin-Etsu Chemical Co.,Ltd

Conventional Neck Model

The Hybrid-Ⅲdummy was developed based on experimental data from volunteers and cadavers. The neck structure is composed of five aluminum plates with hard rubber connecting them each other.

This model was designed for higher-speed forward impact tests, so it needs further consideration to use the model for low-speed rear-end impact tests.

NECK MODEL COMPARATIVE VERIFICATION TEST

Pendulum Test

In order to verify the validity of the K-D Neck Model, several pendulum tests were carried out with the same method as conventional dummy certification tests. And the tests included evaluations whether each cervical sections were suitable for low-speed rear-end sled tests.

Pendulum Teat Result And Discussion

In order to evaluate whether the biomechanical cervical dummy was adequate, the neck rotation angel and neck bending moment were collated and compared with previous documents* so that the evaluation was carried out. (Figure 5.)

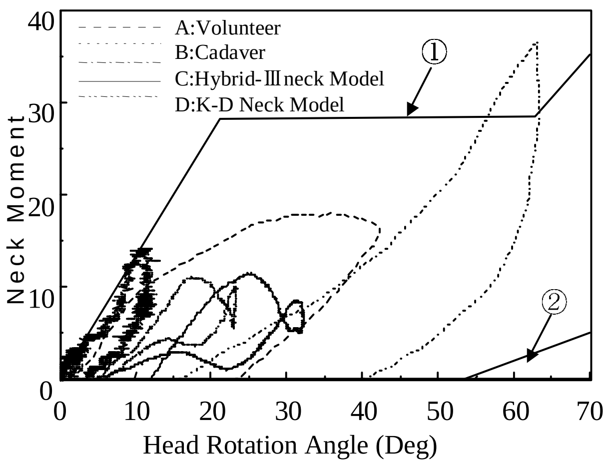


Figure 5. Neck extension torque vs angle responses

The cadaver test data are from results at a collision speed of 16 kilometers per hour and the volunteer test data are from results at 5 to 7 kilometers per hour. The dummy and K-D Neck Model test data are from results at 5 kilometers per hour. The lines ① and ②in figure. 5 are test results obtained from the cadaver and volunteer test. The dummy test results should fall within this area.

* Meltz,H.and Patrick,L..,Strength and Response of the Human Neck, SAE Paper No.710855(1971)

Cadaver

A cadaver has no stiffness in the muscular tissue so the bending moment occurs after a certain increase of the rotation angle

Volunteer

Volunteers are tensed in anticipation of the impact, so that their muscle tissues have stiffness.

Hybrid-ⅢNeck Model

The Hybrid-Ⅲ neck model was mainly designed for use in forward impact tests and has high stiffness suitable for higher-speed forward collision tests. Thus it doesn’t rotate as much as volunteer in low-speed rear-end collisions.

K-D Neck Model

The head rotation angle of the K-D Neck Model is wider than the one of the other models, in spite of a smaller bending moment. Therefore, the K-D Neck Model is less stiff than the Hybrid-Ⅲ neck model.

Based on the above results, we concluded that the K-D Neck Model had more flexibility compared with the other dummy models. Whiplash injury also occurs when the occupant does not anticipate a collision, so muscle strain or contraction is not considered as a significant factor. In other words, the K-D Neck Model simulates a occupant in no anticipation of a collision.

SLED TEST

In the next step of the experiments, sled tests were carried out using the K-D Neck Model and the Hybrid-Ⅲ dummy neck model. The K-D Neck Model was incorporated into the Hybrid III type dummy and low-speed rear-end collision sled tests were carried out with a conventional passenger seat. Fig. 4 is a photograph of the K-D Neck Model used in the tests. The small black points on the cervical vertebra are image analysis points. In these tests, each cervical movements were analyzed.

A driver seat was affixed to the sled as shown in figure 6. A Hybrid-Ⅲ 50th percentile dummy was used and restrained with a seat belt. Test conditions are shown in Table 1.

Sled Test Results And Discusion

Sled tests were held to obtain cervical movements by high speed video pictures at a speed of 8 kilometers per hour .

Table 1. Test condition

Velocity (ΔV)	8km/h
Seat	Frontal driver seat
Headrestraint	Equipped
Dummy model	Hybrid-Ⅲ50th percentile dummy

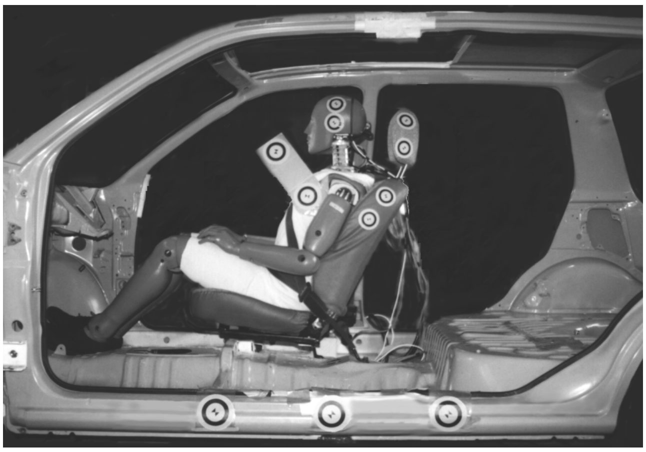


Figure 6. Sled test

Measuring Method Of Shear Displacements

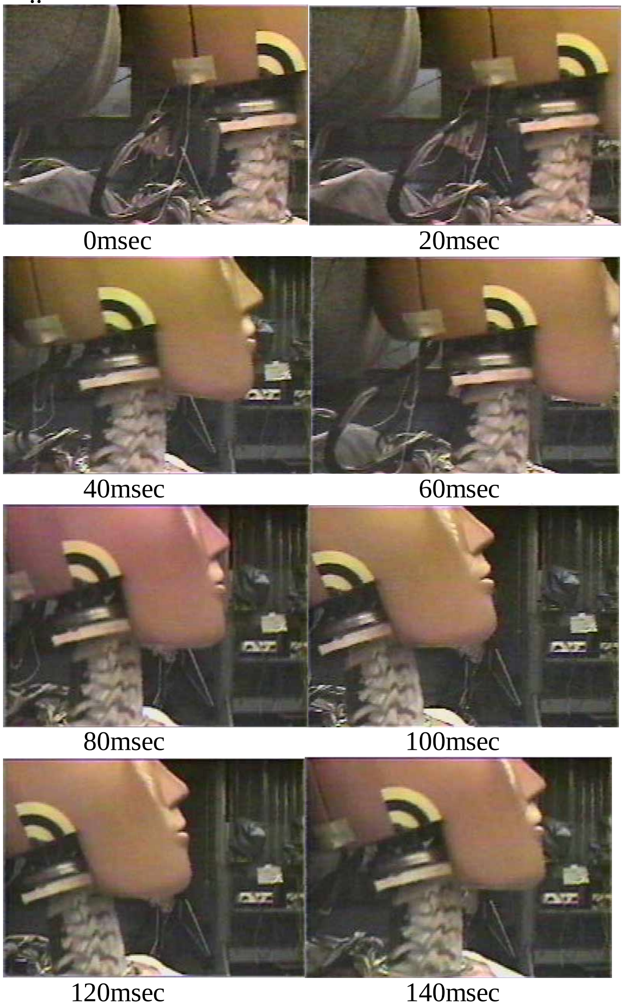


Figure7.Highspeed video camera image

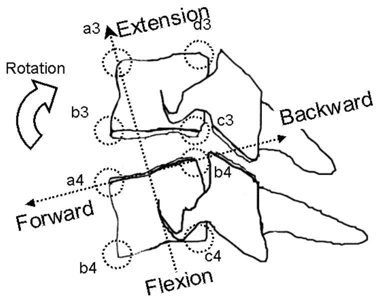
Longitudinal and lateral cervical vertebra movements can be measured over time using the black points on the cervical vertebra as cervical vertebra behavior analysis marks.

In this test, with a high-speed video camera clamped to a truck, the displacement distances in the longitudinal and lateral directions of C2, C3, C4, C5, C6 were measured every 1 msec and photographs were automatically analyzed by computer.

Measured Results Of Cervical Vertebra Displacements

Fig.9 and Fig.10 show results from cervical vertebra displacements in the forward vs. backward direction and also extension vs. flexion direction for △V = 8km/h in a passenger seat affixed with the head restraint. Figure 8 shows the directions of each cervical movements.

In these graphs, " Cn – Cn + 1" is used as the code showing displacement in cervical vertebras. The code "C2 - C3" for instance indicates the C2 displacement distance for C3. These figures show that maximum displacement of each cervical vertebra generally occurs within an interval 130 to 150 msec immediately after the rear-end collision.



Fifure 8. Direction of cervical movements

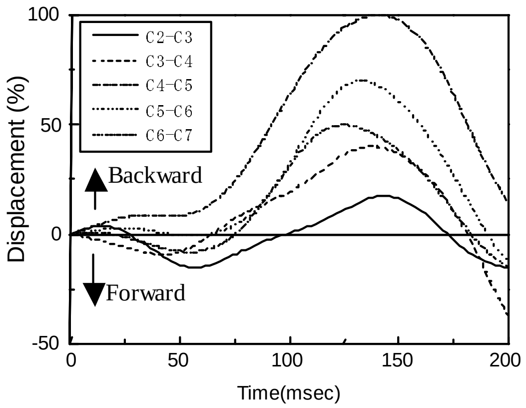


Figure 9. Lateral cervical displacement distances in a conventional seat

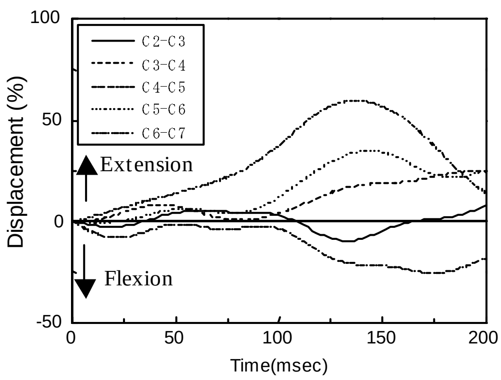


Figure10 . Longitudinal cervical displacement distances in a conventional seat

3-D textile connects each cervical vertebra and is elastic. Therefore, each cervical vertebra can move separately and freely to some extent. The head equipped on the K-D Neck Model was moving backward when the torso of the HybridⅢ dummy was pushed forward by the reaction force of the seat back. Thus, since the lower cervical vertebrae moved forward and the upper cervical vertebrae moved backward, it is supposed that shear displacement in the plane of the intervertebral disks was observed between C5 and C6. Consequently, the head remained back due to the inertia after contacting the headrestraint, while the torso continued to move forward. Therefore, the whole neck came to move forward and shear displacement appeared between C2 and C3.

Fig.7 shows one example of high-speed video images in these tests, and consequently we believe that this so-called "shear displacement in the plane of the intervertebral disks " occurs between the cervical vertebraes. This phenomenon was not observed in the neck sections of the Hybrid-Ⅲ neck. We also hypothesize that this phenomenon is responsible for causing whiplash injuries.

It has been recognized that hyperextension is the important cause of whiplash injuries. However, in recent studies, it has been reported that there are other injury mechanisms, such as the formation of the S-shape. As mentioned previously, in the sled test by using the K-D Neck Model in low-speed rear-end collisions, whiplash motion and S-shape were naturally observed. Furthermore, shear displacements in the plane of the intervertebral disks were found. Therefore, it is supposed that shear displacements may occur in rear-end collisions and would be one of the most important causes of the mechanism of whiplash injuries.

NUMERICAL ANALYSIS WITH FEM

To confirm that the sled tests with the K-D Neck Model simulate the human volunteers' neck movement well, we prepared some FEM models with muscles to verify the fidelity of the K-D Neck

Model.

It is impossible and not allowed to use the real passengers who are unaware of collision. Usually, volunteers should be aware of collisions and avoid themselves suffering neck injuries so that their muscles could make their necks more rigid. But any active muscles systems are not able to realize in the cervical neck models.

In order to solve this problem and also to consider carefully the muscles effects, we made the structure of the FEM neck model including muscle elements shown in figure11. The properties of muscle elements were mechanically described in the formula defines as 'Hill type muscle model' shown in figure12.

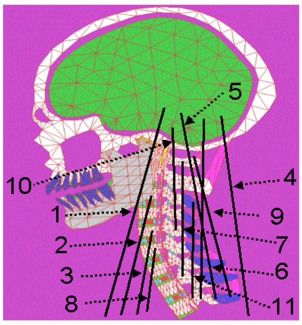
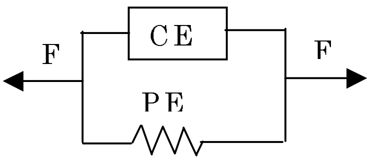


Figure 11. FEM model with muscles



Muscle force F = Fce + Fpe

CE : Contractile element

PE : Parallel elastic element

Figure 12. Hill-type muscle model

The active force (Fce) was defined in the formula shoen in figure 13.

$$F_{CE} = A\,F_{max}\,f_H(v_r)\,f_L(l_r)$$

$l_r = l/l_{ref}$ l : muscle length

l_{ref} : optimum length

$v_r = v/V_{max}$ v : lengthening velocity

V_{max} : maximum shortening velocity

F_{max} : muscular force during maximal activation

A : active state (muscle's activation level)
A=1:maximal activation, A=0:resting state

Figure 13. Definition of active force Fce(1)

And the active force versus velocity relationship is shown in figure 14.

$$F_{CE} = A\,F_{max}\,f_H(v_r)\,f_L(l_r)$$

f_H : Active force-velocity relationship
(Hill curve)

$$f_H(v_r) = \begin{cases} 0 & (v_r \leq -1) \\ (1+v_r)/(1-v_r/CE_{sh}) & (-1 < v_r \leq 0) \\ (1+v_r CE_{ml}/CE_{shl})/(1-v_r/CE_{shl}) & (v_r > 0) \end{cases}$$

$$f_L(l_r) = \exp(-(l_r-1)/S_k)^2)$$

Active force-length relationship

Figure 14. Definition of active force Fce(2)

The passive elastic force (F PE) is shown in figure15.

$$F_{PE} = F_{max}\,f_p(l_r)$$

$$f_p(lr) = \begin{cases} k_1(\exp(k_2(l_r-1)-1) & (l_r>1) \\ 0 & (l_r<1) \end{cases}$$

$$k_1 = 1/(\exp(PE_{sh})-1)$$
$$k_2 = PE_{sh}/PE_{xm}$$

Passive force-length relationship

Figure15. Passive elastic force FPE

Figure 16 shows the results of the FEM analyses.

The longitudinal axis is horizontal displacement of head and the lateral axis is 'Time' after collision.

The cadaver has definitely no active muscle forces, so its active state of muscles A must be 0.

If the muscle active state A = 1, the model indicates the neck movement with the most rigid muscles.

From the FEM results, it was found that the average behavior of the volunteer's necks was similar to the model for A=0.8, and this result reveals that the volunteers have rather (pretty) stronger tensile stresses in their neck muscles.

While the K-D Neck Model was similar to the model A=0.5, and this result means the K-D Neck Model adequately simulates the neck without any anticipation to rear-end collisions. We consider that the situation of 'A=0.5' means not so rigid as tensed volunteers but relaxed volunteers.

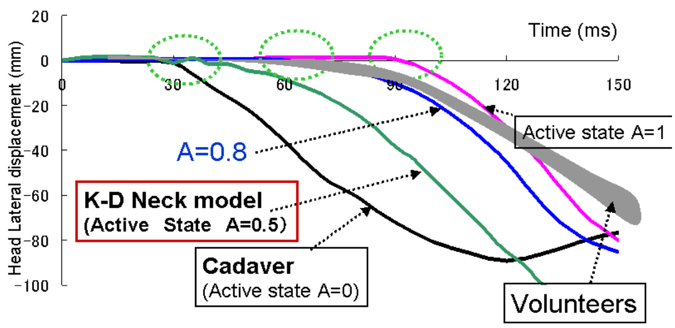


Figure 16 Horizontal displacement of head.

We may conclude that these FEM models with muscles showed the K-D Neck Model had better biomechanical fidelity of the human neck behavior under impacts.

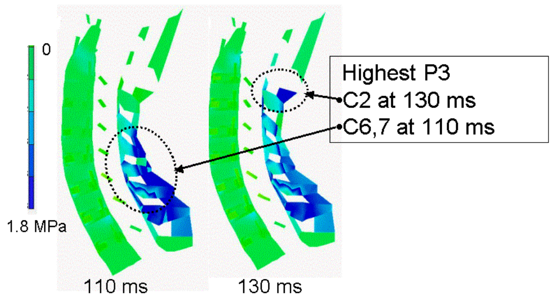


Figure 17.Minimum principal stress

Figure 17 shows the minimum principal stresses around the cervical vertebrae model with the stress peaks around C6, C7 area at 110 milliseconds and around C2 area at 130 milliseconds.

These results agree with the shear displacement phenomena in location and timing as shown before.

NEW SEAT STRUCTURE

We considered that the rapid (quick) support of the passengers' head should reduce whiplash injuries by lessening shear displacement in the cervical spines.

Figure 18 is the structure of the new passenger seat system we designed.

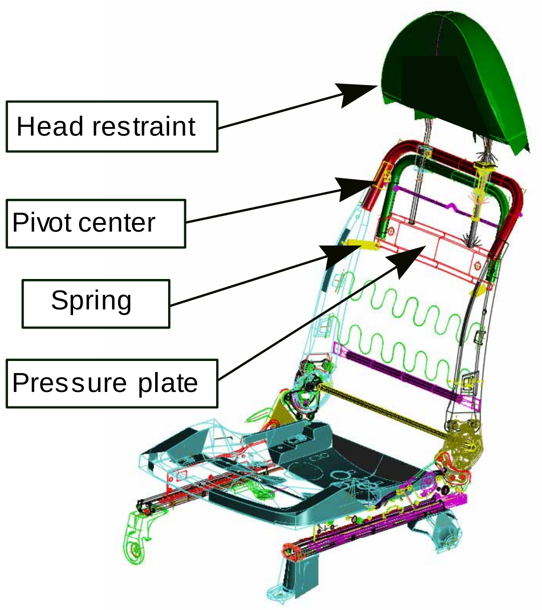


Figure 18. New seat structure

The headrestraint swings forward after low-speed rear-end collisions. By the sled experiments, we measured the dummy's lateral and longitudinal cervical movement and observed that the faster support of the dummy head was effective to reduce the displacement between each cervical vertebra .

A head restraint and a pressure plate coupled to the headrestraint are housed within the seatback. When the vehicle occupant is moved backwards during a rear-end collision, the passenger's back intrudes into the setback. The force of the passenger's body moves the pressure plate rearward. Near the swivel center set at the upper part of the seatback frame, the headrestraint linked coupled to the pressure plate then moves forward to support the back of the occupant's head immediately. The headrestraint swinging mechanism in this way functions to reduce whiplash injuries.

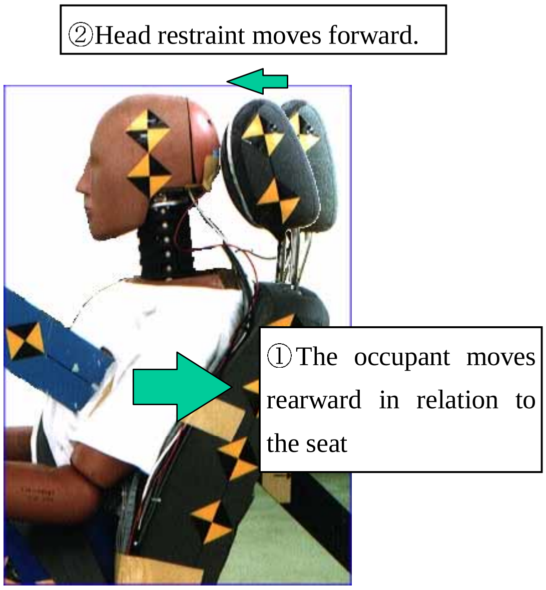


Figure 19. Mechanism of dynamic support head restraint

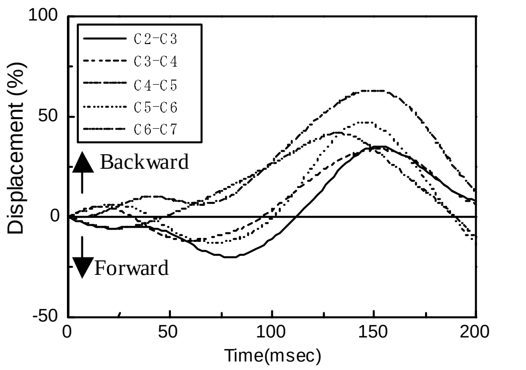


Figure 20. Lateral cervical displacement distances in a new seat system

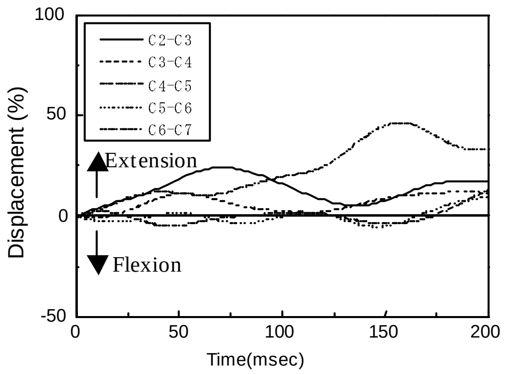


Figure 21. Longitudinal cervical displacement distances in a new seat system

Fig. 20 and Fig. 21 show measurement results obtained with the whiplash reduction passenger seat. These figures demonstrate that the maximum displacement in the cervical vertebra is generated within an interval of 130 to 150 msec immediately after the rear-end collision, just the same as with the conventional passenger seat mentioned above.

However with the new whiplash reduction seat, the amount of displacement is greatly reduced in the lateral direction as 38% and in the longitudinal direction as 90%. Analysis results clearly demonstrate in fig. 22 and fig. 23.

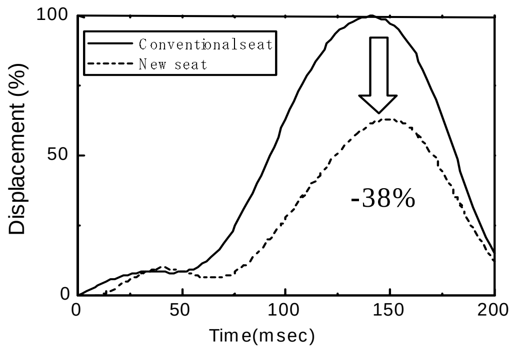


Figure 22.The lateral cervical displacement reduction effect

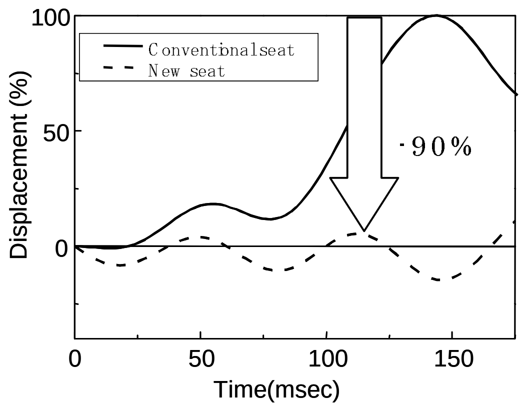


Figure 23. The longitudinal cervical displacement reduction effect

CONCLUSION

This paper describes the sled tests using the K-D Neck Model .The detailed analyses were further made about the behavior of the vehicle occupants in the low-speed rear-end collision using the K-D Neck Model by focusing particularly on the phenomena of cervical vertebra displacements in the lateral and the longitudinal directions. As the results of the analyses, we draw the following conclusions.

We succeeded to observe the phenomena of the each cervical displacements in the lateral and longitudinal directions with the K-D Neck Model.

The forward and rearward displacements of the cervical vertebra hypothesized to be a major factor in causing whiplash injury has been reduced 38% laterally and 90% longitudinally between C4 and C5 by using the whiplash reduction passenger seat.

We proved it possible in the sled experiments with the K-D Neck Model mounted on the Hybrid-Ⅲ dummy to simulate the phenomena of the cervical displacements in the longitudinal and lateral directions, which is difficult to be reproduced with conventional neck models..

The displacement phenomena of cervical vertebraes, which was difficult to be measured in sled experiments with cadavers nor with actual human bodies nor with the volunteers in the past, can be recognized in detail from the analyses of images recorded by the high speed video camera. Consequently, it becomes possible to measure quantitatively the cervical displacement in the longitudinal and the lateral direction that is hypothesized causing whiplash injuries.

Finally, the K-D Neck Model is proved to be the effective device which can repeatedly simulate, at the comparatively low cost, the neck behavior of a vehicle occupant involved in the low-speed rear-end collision. We intend to study and improve the K-D Neck Model further in the future to apply the model to the investigation of the mechanism causing whiplash injuries of vehicle occupants and to the research and the development of the restraint system to reduce whiplash injuries.

REFERENCES

1. Japan Automobile Research Institute, Inc., “Research of a traffic accident”, (1992)
2. Japan Automobile Research Institute, Inc., “Research of a traffic accident”, p 85 (1986)
3. Richard S.Snell, ”Snell Clinical Anatomy”, Medical Science International Inc., in Japanese, p718 (1983)
4. Hiroshi Ouchi et al, “Partial charge anatomy”, Kanahara Publication, in Japanese, p27-33,p181-185 (1950)
5. Yoshihito Ikada, “Biomaterial first step”, Academic society publication center, in Japanese, p76 (1993)
6. J.Chazal et al, “Biomechanical Properties of Spinal Ligaments and a Histological Study of the Supraspinal Ligament in Traction”, J.Biomechanical, Vol.18, No.3, p167-176 (1985)
7. Kotohito Yoshimura, “Physiologically human body”, Kougakkann, in Japanese, p165 (1981)
8. Michio Inokai, “Exercise physiological first step”, Anjyusyoin, in Japanese, p128-129 (1963)
9. Meltz, H.and patrick,L., “Strength and Response of the Human Neck” ,SAE Paper No.710855 (1971)
10. Sadami Tstutsumi, Hiroaki Yoshida, Yoichi Miyajima, “Impact Analyses of Whiplash Neck Behaviors in Rear-End Collisions”, JSME Paper No.96-1088 (1997)
11. Hiroaki Yoshida, Yoichi Miyajima, Sadami Tsutsumi, “Numerical and Experimental Impact Analysis of Neck Behaviors in Rear-end Collisions”, Proceedings of the International Conference on New Frontiers in Biomechanical Engineering, p277-280 (1997)
12. Hiroaki Yoshida, Yoichi Miyajima and Sadami Tsutsumi, “Impact Analysis of Whiplash Injuries in Rear-end Collisions”, AMSE

(INTERNATIONAL MECHANICAL ENGINEERING CONGRESS AND EXPOSITION), BED Vol.39, p147-148 (1998)

13. The Marine & Fire Insurance Association of Japan. INC, “ Traffic accidents situation in Japan analyzed from the insurance payment data 2002” (2002)
14. Hiroaki Yoshida, Sadami Tsutsumi, Experimental analysis of a new flexible neck model for low-speed rear-end collisions, Accident Analysis and Prevention, Vol.33, 305-312 (2001)
15. Hiroaki Yoshida, Sadami Tsutsumi, Finite element analysis using muscles elements and experimental analysis with a new flexible neck model of whiplash injuries in rear-end collisions, SAE paper No.2002-01-0021 (SP-1665, Impact Biomechanics) (2002)